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TECHNICAL NOTE

D-580

SURFACE PRESSURE DISTRIBUTIONS WITH A SONIC JET NORMAL TO ADJACENT FLAT SURFACES AT MACH 2.92 TO 6.4

By Robert W. Cubbison, Bernhard H. Anderson, and James J. Ward

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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TECHNICAL NOTE D-580

SURFACE PRESSURE DISTRIBUTIONS WITH A SONIC JET NORMAL TO ADJACENT FLAT SURFACES AT MACH 2.92 TO 6.4

By Robert W. Cubbison, Bernhard H. Anderson,
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SUMMARY

An investigation was made to determine the interference effects on surface pressure distributions caused by a sonic jet exiting normal to the surface. Two configurations, a flat plate and an arrow-wing reentry-type vehicle, with sonic nozzles near the leading edge were tested over a range of pressure ratios and Reynolds numbers for Mach numbers from 2.92 to 6.4.

The data indicate that jet pressure ratio had considerable effect on the pressure levels and distributions on both configurations. Also, for a constant jet pressure ratio, the free-stream Mach number effect on the distributions and levels was quite large. Over the limited range investigated, the effect of Reynolds number at constant Mach number and pressure ratio was small compared to the Mach number and pressure ratio effect.

INTRODUCTION

As operating altitude is increased, conventional aerodynamic control systems become inadequate for attitude control. In this low-dynamic-pressure region, it becomes necessary either to augment the conventional system or to use an independent set of controls such as reaction jets. The use of such controls creates a surface pressure field because of the interaction of the exiting jet and the local flow. A generalized experimental study of this jet-stream interaction is needed in order to estimate the attendant thrust augmentation and stability characteristics of specific vehicles.

Several reports have been published which describe the interaction effects produced by jets exiting parallel to a surface (refs. 1 to 3). Additional information is available on a jet exhausting normal to the stream direction near the base of an axisymmetric model (ref. 4). The present experimental investigation was made to determine the effects of pressure ratio, free-stream Mach number, and Reynolds number on the external pressure field due to the jet from a sonic nozzle located near the leading edge and normal to adjacent surfaces. The study included a sharp-edge flat-plate model and a blunt-nose arrow-wing reentry-type vehicle to illustrate the effect of the two different leading-edge geometries.

The tests were conducted at Mach numbers of 2.92 to 6.4 with various Reynolds numbers between 0.84×10^6 and 7.78×10^6 per foot. Jet total pressure was varied from 50 to 440 pounds per square inch gage. The pressure altitude was varied between 55,000 and 115,000 feet.

SYMBOLS

C_p pressure coefficient, $(p - p_0)/q_0$

M Mach number

P total pressure

p static pressure

q dynamic pressure

Subscripts:

j jet

0 free stream

APPARATUS AND PROCEDURE

Details of the flat-plate and the arrow-wing configuration and their respective instrumentation layouts are shown in figure 1. A 0.062-inch-exit-diameter sonic nozzle was located on the centerline 40.3 nozzle-exit diameters (2.5 in.) downstream of the leading edge of the flat plate and 35.5 diameters (2.2 in.) downstream of the vertex of the arrow wing. In each case the control jet was mounted flush with the adjacent surface. Cold air pressurized to 440 pounds per square inch was discharged through the nozzles.

The static-pressure instrumentation on the flat plate extended 32.2 nozzle-exit diameters (2.0 in.) upstream, 100.8 diameters (6.25 in.) downstream, and 60.5 diameters (3.75 in.) spanwise from the nozzle exit. The instrumentation in the vicinity of the jet on the arrow wing was similar to that on the flat plate. The instrumented region on this configuration extended 19.4 nozzle-exit diameters upstream, 16 diameters downstream, and 6.1 diameters spanwise from the nozzle exit.

The width (11.625 in.) of the flat plate was such to ensure two-dimensional flow around the reaction control jet. As shown in figure 1(a) the Mach cone only influences the most outward static taps. The re-entry configuration consisted of a highly swept aspect-ratio-1.76 arrow wing with a canopylike protuberance installed to house the model support system. The wing was 0.4 inch thick with a rounded nose and leading edge with an angle of sweep of 74°. Both models were sting-supported in the tunnel.

The test was conducted in the 1- by 1-foot variable-Mach-number (2.92 to 4.84) tunnel and in the 22-inch-diameter Mach 6.4 tunnel. A limited Reynolds number range was investigated with jet total pressures varied from 50 to 440 pounds per square inch.

RESULTS AND DISCUSSION

The flow pattern resulting from the interaction of a sonic jet (at 90° to the surface) with the local boundary layer and supersonic flow is illustrated in figure 2. This, of course, is only a centerline representation of what is actually a three-dimensional flow phenomenon. With the nozzles located near the leading edge and for the range of free-stream conditions studied, a laminar boundary layer would be anticipated ahead of the jet at jet-off conditions. The presence of the expanding jet causes a strong bow wave ahead of the jet and extensive boundary-layer separation surrounding the jet. Mass flow from both the jet and the free stream is entrained in this separated region. In the centerline plane upstream of the jet the two flows create a pair of counterrotating vortices with the adjacent streamlines impinging on the surface causing a region of high local pressure (stagnation point) ahead of the jet. Fore and aft of the stagnation point, regions of low static pressure are created. Forward of the point of maximum pressure, the pressure rise due to boundary-layer separation should be relatively constant. Because of jet overexpansion the pressures drop below free-stream values over a portion of the surface downstream of the jet. Further downstream the flow is recompressed through a shock system back to free-stream static pressure.

Contour plots of constant pressure coefficient on the flat plate are shown in figure 3 for a free-stream Mach number of 2.92 and a Reynolds number of 0.84×10^6 per foot. A small region of high pressures surrounding the jet and trailing out along the shock wave (locus of maximum C_p) can be seen in figure 3(a). Also a relatively large region (enclosed by the line of zero C_p) where the local static pressures are below the free-stream value is shown downstream of the jet. As the pressure ratio

P_j/p_0 is increased, the pressure level increases ahead of the jet and decreases downstream of the jet (figs. 3(b) and (c)). The areas of constant C_p increase in size, and regions of larger pressure coefficients, both positive and negative, appear within their respective areas. Contours at Mach 4.84 are not presented; however, similar trends were also observed.

The effect of pressure ratio on the pressure distribution over the flat plate at Mach numbers of 2.92 and 4.84 is summarized in figure 4. At both Mach numbers the locus of maximum pressure moves upstream with increasing pressure ratio. Also the region of negative pressure coefficient increases in area and extends farther downstream. This is primarily due to the displacement effect necessary to satisfy continuity. These trends are much more pronounced at the higher Mach number (fig. 4(b)).

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Flow patterns and corresponding centerline pressure distributions for both the flat-plate and arrow-wing configurations are shown for a range of flight Mach numbers and jet pressure ratios in figures 5 to 9. Dotted lines have been sketched on the schlieren photographs to define the interaction region and the attendent shock structure as indicated in figure 2. The point of incipient boundary-layer separation is shown both in the photographs and from the pressure distributions. As the pressure ratio is increased, the separation point moves upstream on the flat plate, and the jet penetrates deeper into the local supersonic stream because of increased jet mass flow entering the interaction region (figs. 5 and 7). At a Mach number of 4.84, data (not presented here) indicate the point of separation moved forward to the plate leading edge at a pressure ratio somewhere between 1400 and 2600. Downstream of the nozzle the jet flow eventually reattaches, and another boundary layer begins to form. Also, the vortex system created by the interaction of the jet and free stream can be seen flowing around and trailing back essentially parallel to the surface. In contrast to the sharp-edge case, the photographs and data indicate that separation occurred at the leading edge for all jet-on operating conditions with the arrow-wing configuration (figs. 6, 8, and 9). Although the recompression system downstream of the jet is not visible in the schlieren pictures, it can be seen in the pressure distributions. The oscillation of the bow wave apparent in the photographs is associated with the unstable characteristics of the boundary-layer separation. The dotted portions of the fairings of the pressure distributions on these figures as well as the following figures are extrapolations based on an analysis of all the pressure data.

A comparison of the centerline pressure distribution of the flat-plate and arrow-wing configurations for the same operating conditions at Mach numbers of 2.92 and 4.84 is presented in figures 10 and 11. Generally, the trends with pressure ratio are the same for both configurations. Downstream of the jet, the point where the centerline pressure becomes equal to the free-stream value moves away from the jet as the pressure ratio is increased. Ahead of the reaction control jet, the pressure level increases with increasing pressure ratio. The pressure level upstream of the peak values is higher on the arrow-wing configuration because of the bow wave off the blunt leading edge and the higher boundary-layer separation angle. This larger angle results from the jet being located near the nose of the arrow-wing model.

The effect of Reynolds number at constant pressure ratio on both configurations at Mach numbers of 2.92 and 4.84 is illustrated in figure 12. Generally, a small effect (compared to the pressure ratio effect) was noticed on either the flat-plate or arrow-wing configuration at either Mach number for the range of Reynolds numbers investigated.

A change in free-stream Mach number while holding the pressure ratio constant produced a considerable change in the pressure coefficient level at the stagnation point. This trend is shown for both configurations in figure 13. The peak value is reduced because, as the Mach number is increased, there is a decrease in the amount of free-stream mass flow entrained in the separated region. Also because of the lower chamber pressure required to maintain a constant pressure ratio with increasing flight Mach number, there is less jet flow entering the stagnation region. Consequently, the pressure level at the stagnation point is lower because of the lower kinetic energy available in the interaction field. The pressure coefficient level downstream of the jet increases as the flight Mach number is increased because of a decrease in jet overexpansion due to the lower chamber pressures required to maintain a constant pressure ratio.

Figure 13(a) shows that the increasing pressure level downstream of the jet on the arrow-wing configuration at Mach 6.4 resulted in the centerline pressure reaching free-stream static pressure in about 5 jet-exit diameters or 0.4 inch downstream. On the flat plate (fig. 13(b)) the free-stream value of static pressure is not reached for about 90 or 100 jet diameters downstream at Mach 4.84 compared with about 50 diameters at Mach 2.92, although the initial pressure level is higher at the higher Mach number.

CONCLUDING REMARKS

The present study was designed to determine the interference effects on surface pressure distribution with a jet from a sonic nozzle exiting normal to the surface. Two models, one a flat plate and the other an arrow-wing reentry-type configuration with a sonic nozzle located near the leading edge, were investigated over a range of Reynolds numbers, free-stream Mach numbers, and pressure ratios. The results indicate that jet pressure ratio had considerable effect on the surface pressure distributions. Also, variations in free-stream Mach number at constant pressure ratio caused considerable change in pressure level. Over the limited range investigated, the effect of Reynolds number at constant pressure ratio was small compared to either the Mach number or pressure ratio effects.

The data presented here have shown that the interaction field can be quite extensive, the zone of influence of the reaction jet in some cases being as much as 100 nozzle diameters. For any specific application, therefore, it would be necessary to know the detailed vehicle geometry (and thus the area for pressure integration) in order to assess the degree of overall thrust augmentation or loss.

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Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 21, 1960

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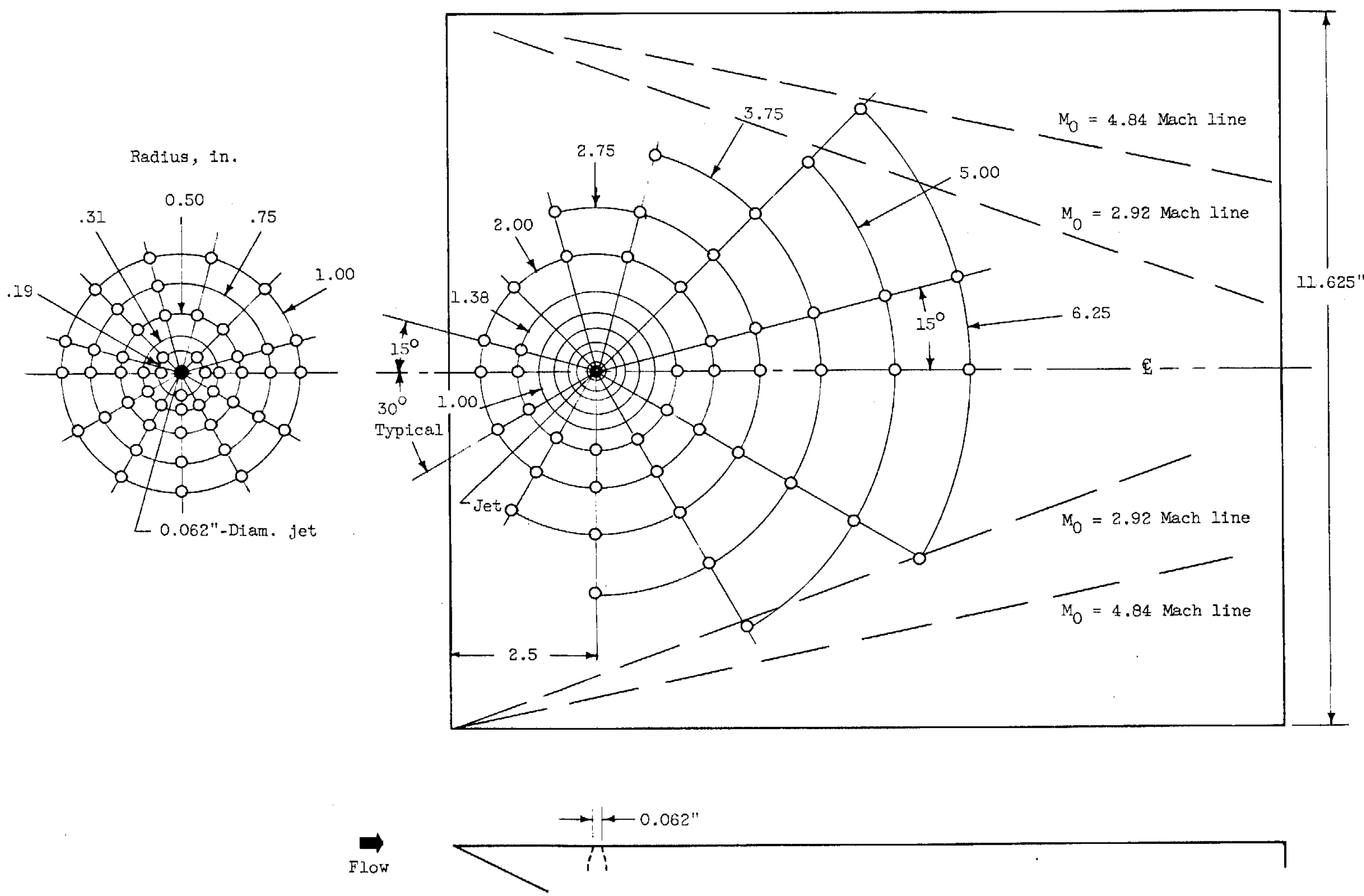
2. Englert, Gerald W., Wasserbauer, Joseph F., and Whalen, Paul: Interaction of a Jet and Flat Plate Located in an Airstream. NACA RM E55G19, 1955.

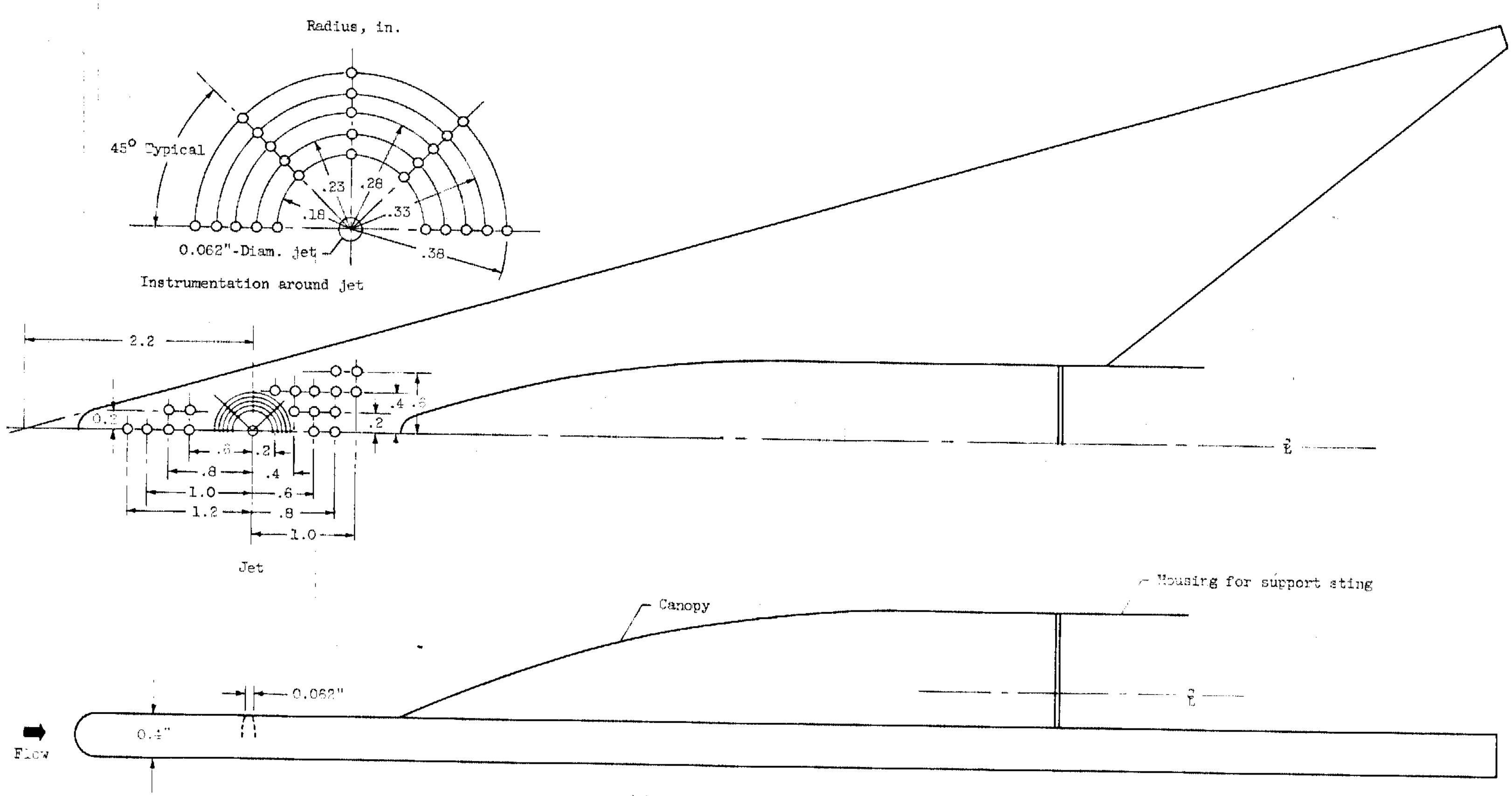
3. Falanga, Ralph A., and Janos, Joseph J.: Pressure Loads Produced on a Flat-Plate Wing by Rocket Jets Exhausting in a Spanwise Direction Below the Wing and Perpendicular to a Free-Stream Flow of Mach Number 2.0. NACA RM L58D09, 1958.

4. Vinson, P. W., Amick, J. L., and Liepman, H. P.: Interaction Effects Produced by Jet Exhausting Laterally Near Base of Ogive-Cylinder Model in Supersonic Main Stream. NASA MEMO 12-5-58W, 1959.



(a) Flat-plate configuration.

Figure 1. - Test configurations and instrumentation.



(b) Arrow-wing configuration.

Figure 1. - Concluded. Test configurations and instrumentation.

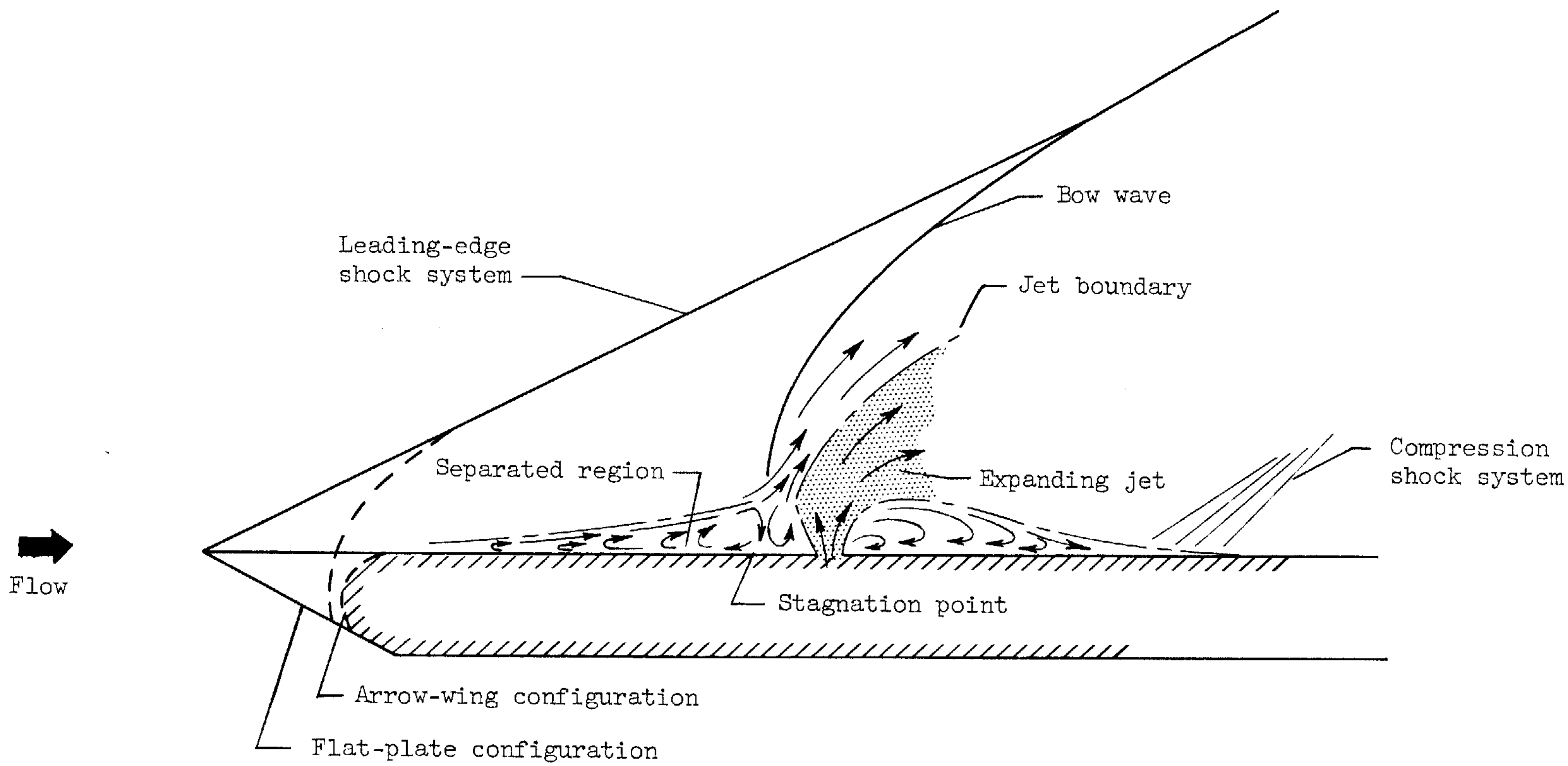
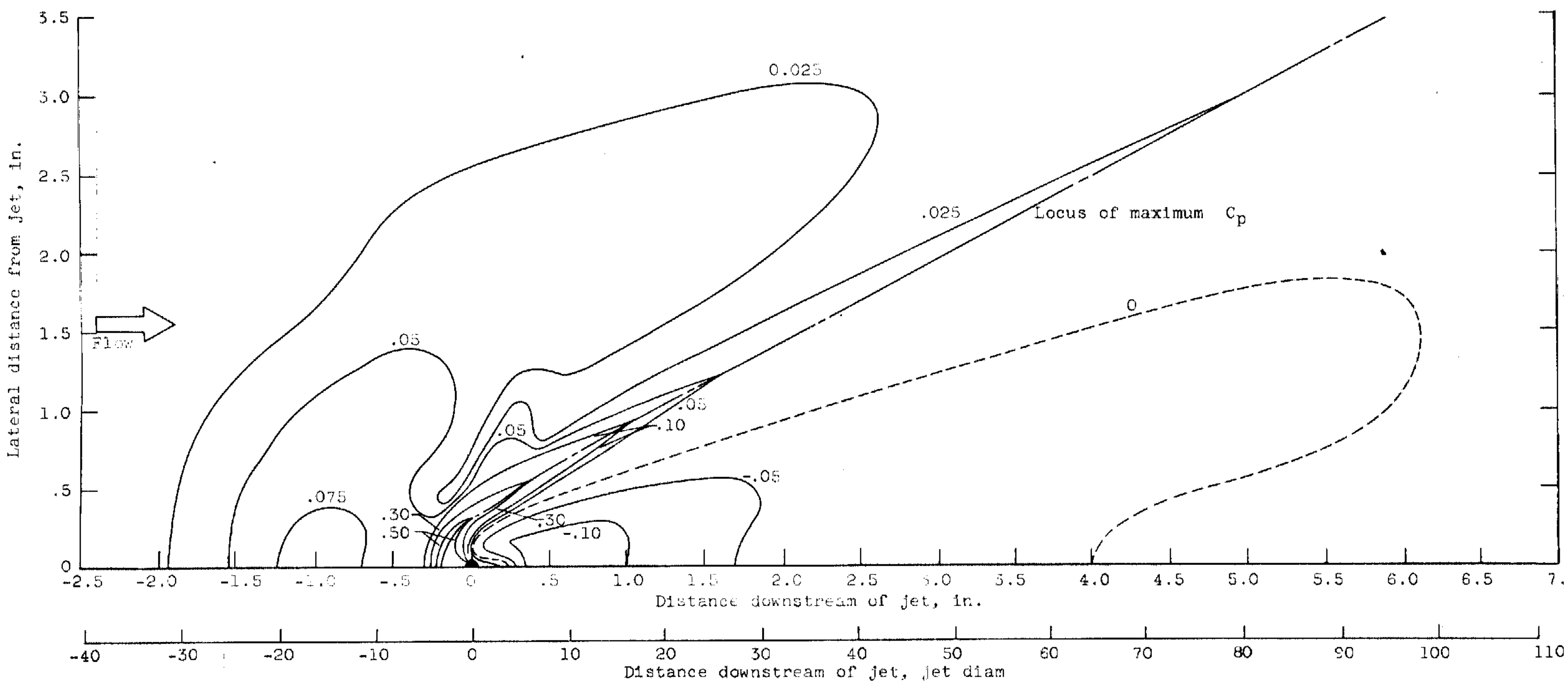
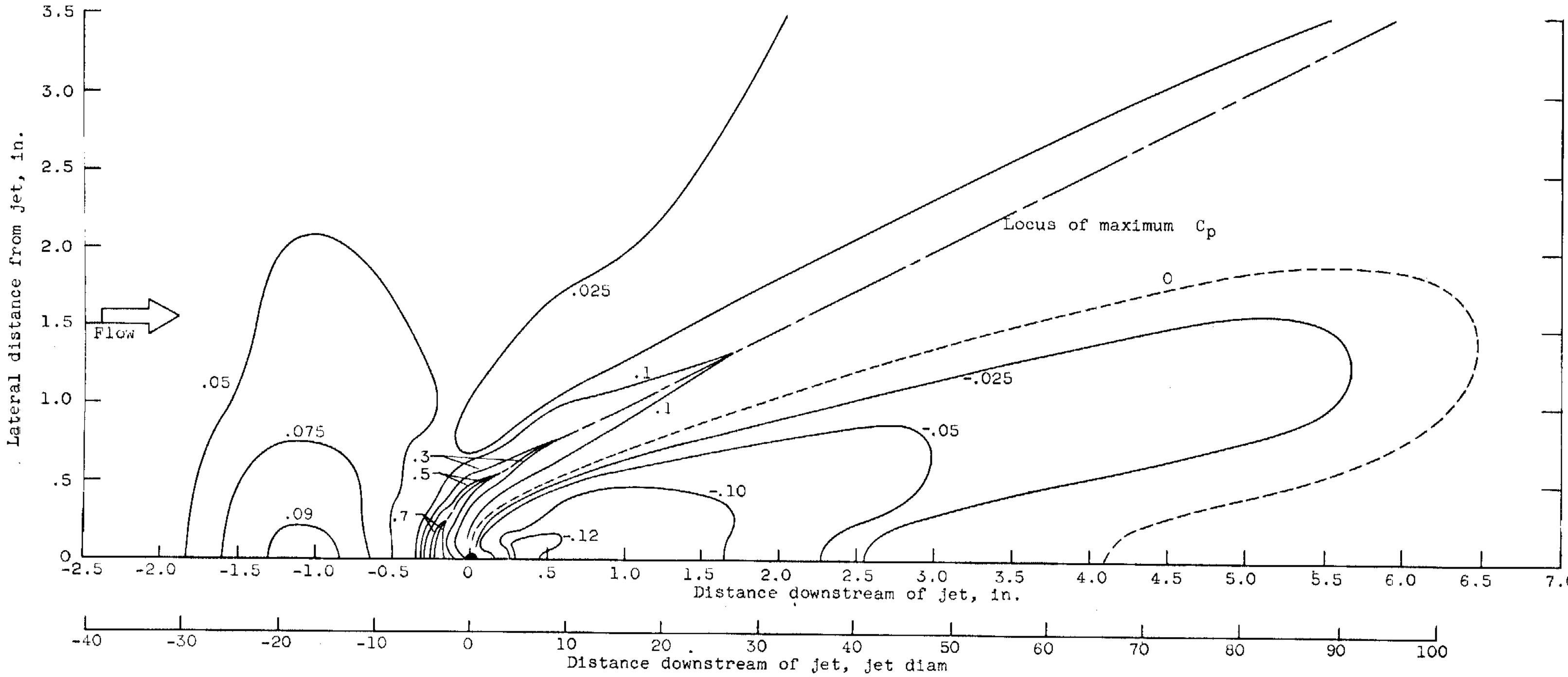


Figure 2. - Schematic flow diagram in vicinity of jet.



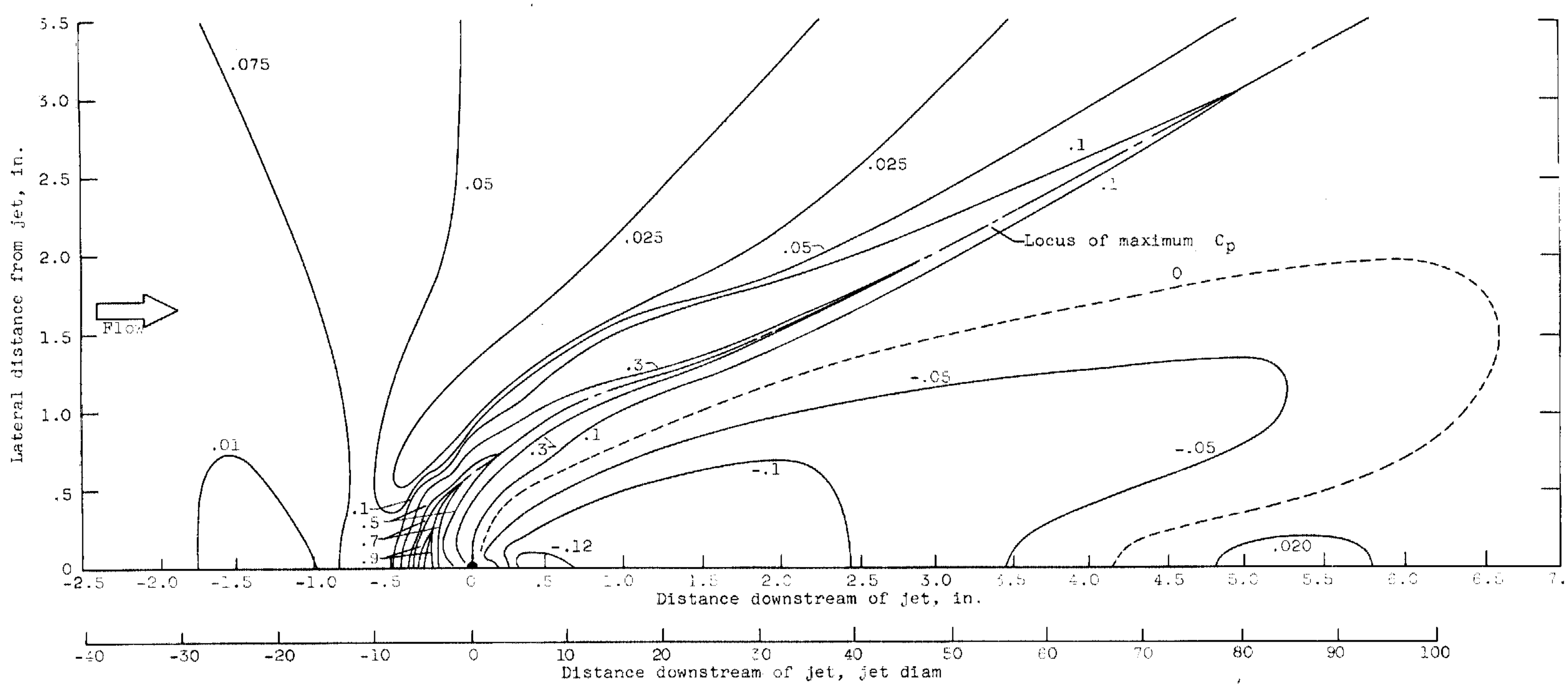
(a) $P_j/p_0 = 677$.

Figure 3. - Pressure coefficient contours on flat-plate configuration at Mach number of 2.92 and Reynolds number of 0.84×10^6 per foot.



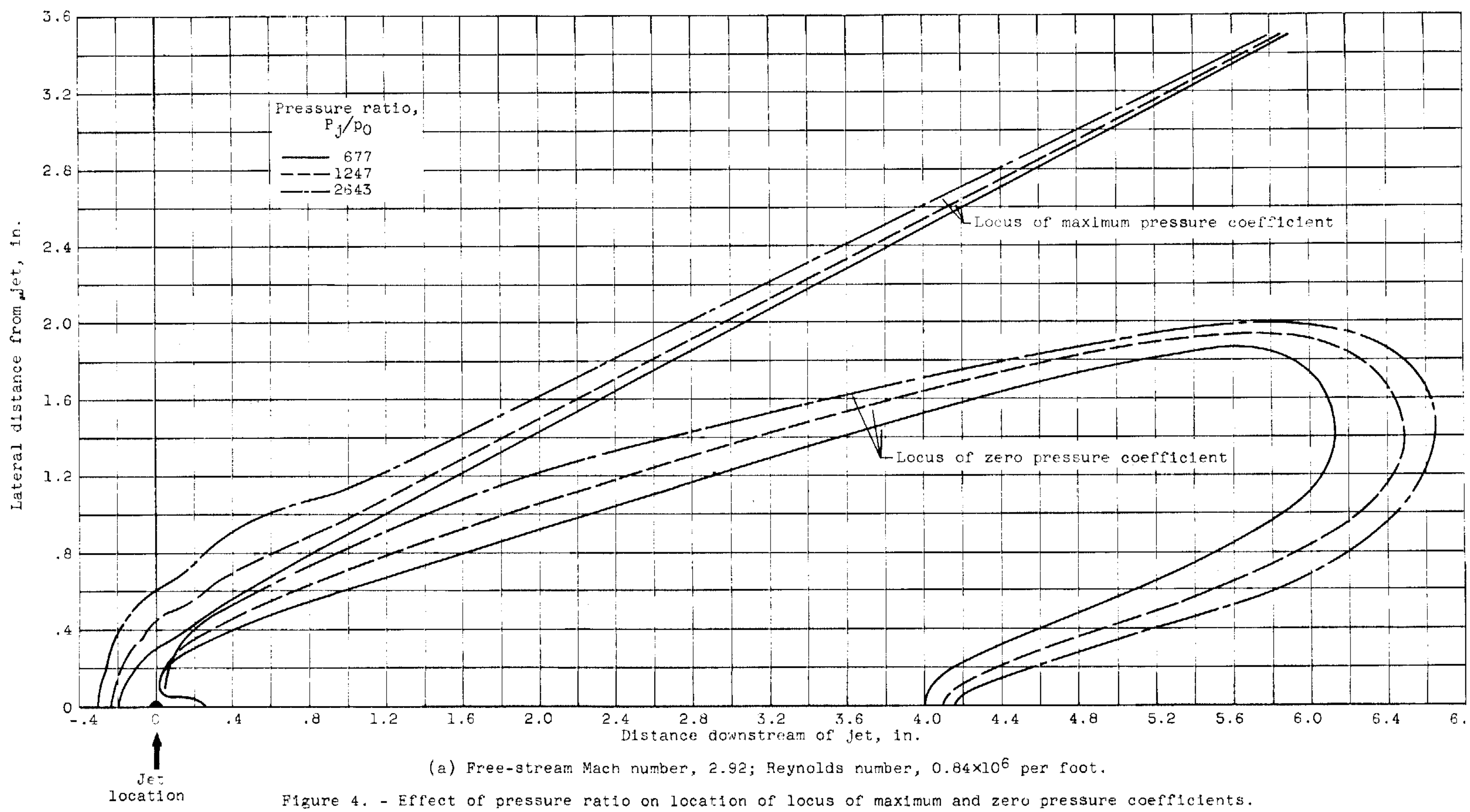
(b) $p_j/p_0 = 1247$.

Figure 3. - Continued. Pressure coefficient contours on flat-plate configuration at Mach number of 2.92 and Reynolds number of 0.84×10^6 per foot.



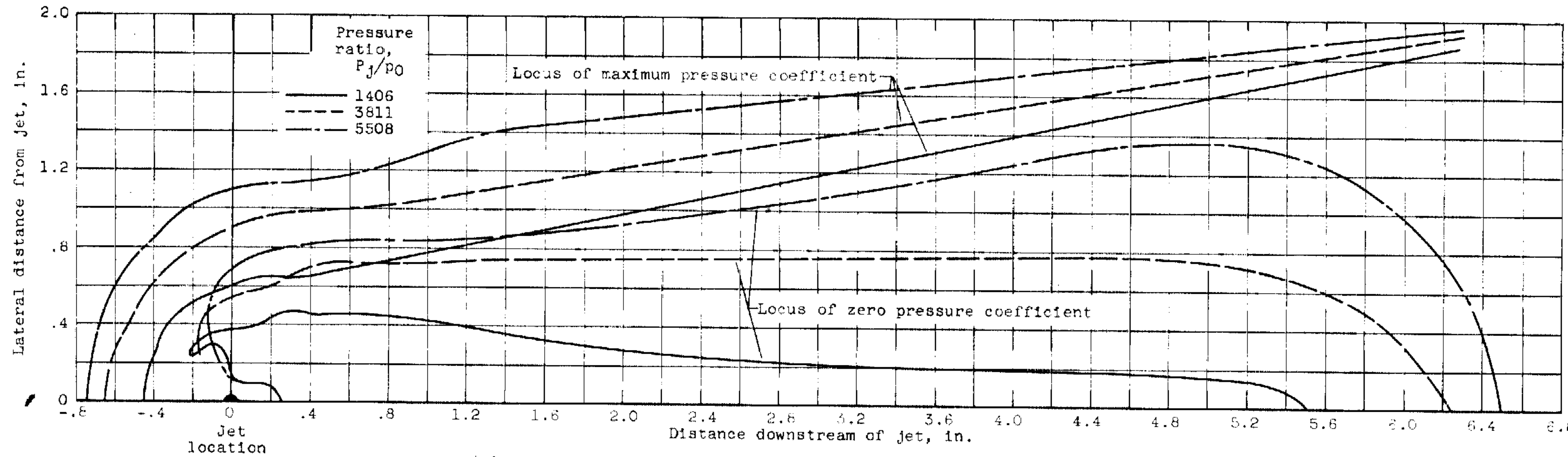
(c) $p_j/p_0 = 2643$.

Figure 3. - Concluded. Pressure coefficient contours on flat-plate configuration at Mach number of 2.92 and Reynolds number of 0.84×10^{6} per foot.



(a) Free-stream Mach number, 2.92; Reynolds number, 0.84×10^6 per foot.

Figure 4. - Effect of pressure ratio on location of locus of maximum and zero pressure coefficients.



(b) Free-stream Mach number, 4.84; Reynolds number, 1.4×10^6 per foot.

Figure 4. - Concluded. Effect of pressure ratio on location of locus of maximum and zero pressure coefficients.

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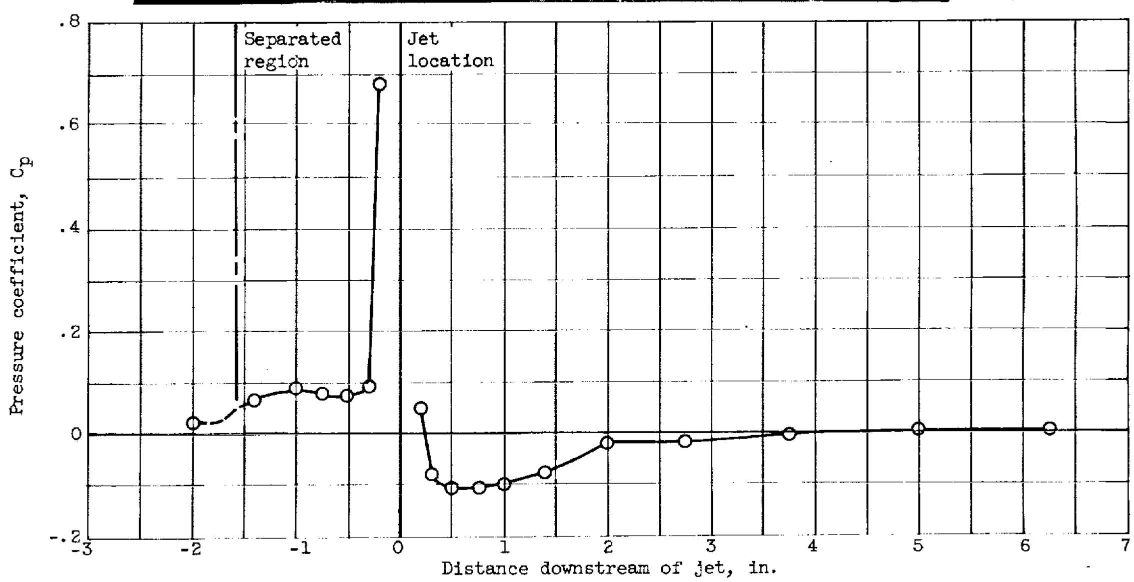
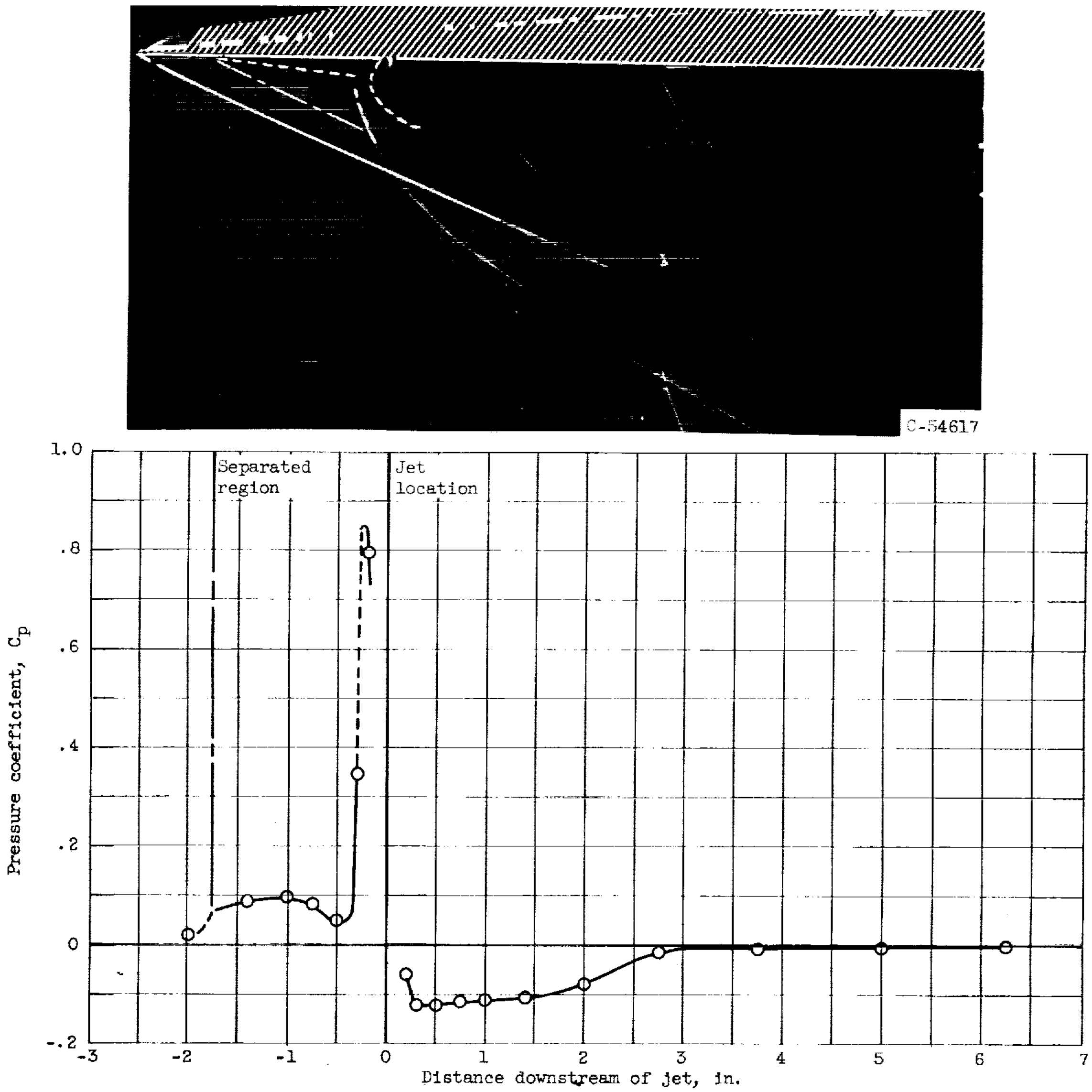


(a) $P_j/p_0 = 677$.

Figure 5. - Schlieren photographs of flat-plate configuration at Mach number of 2.92 and Reynolds number of 0.84×10^6 per foot.



(b) $P_j/p_0 = 1247$.

Figure 5. - Continued. Schlieren photographs of flat-plate configuration at Mach number of 2.92 and Reynolds number of 0.84×10^6 per foot.

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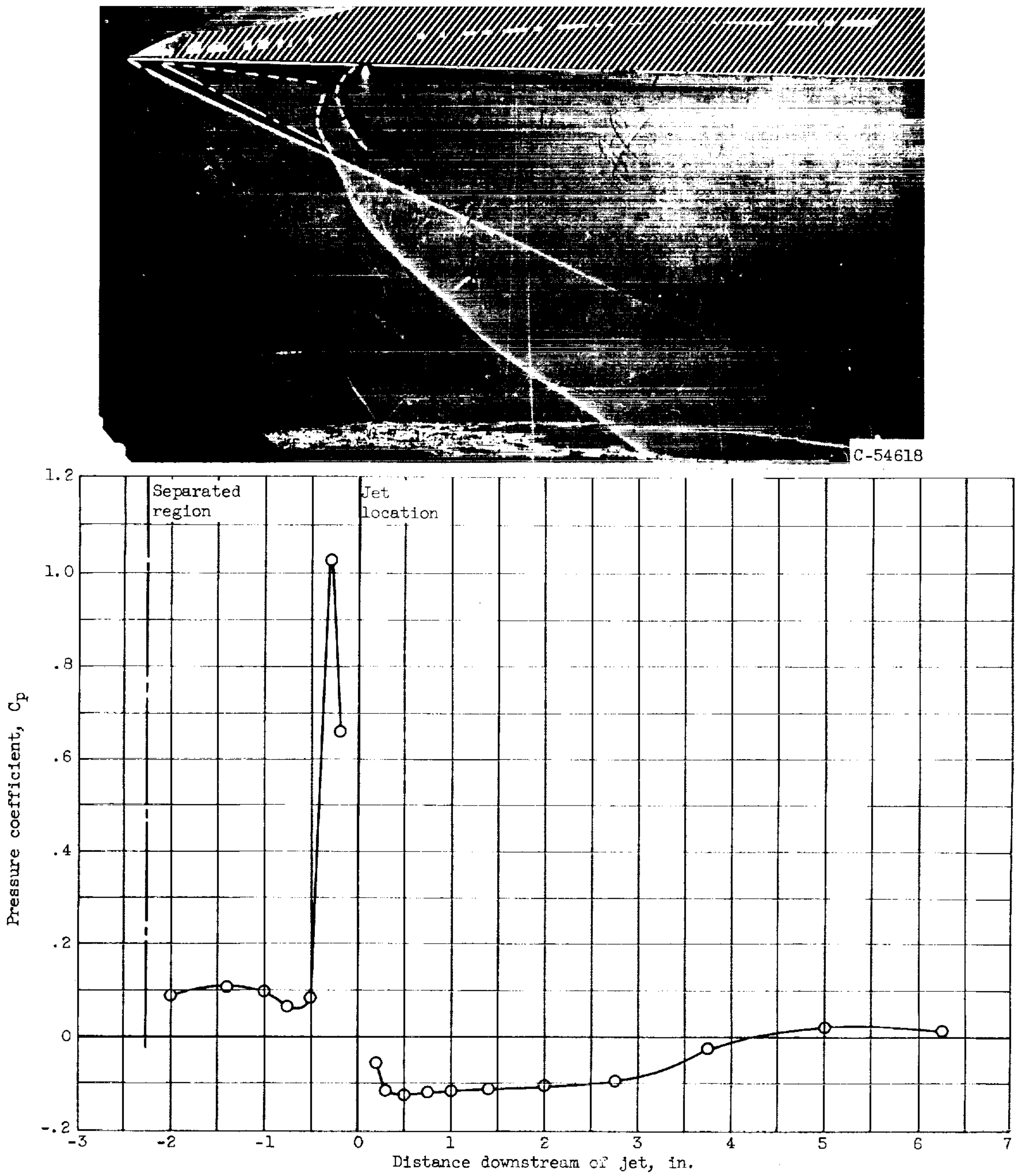
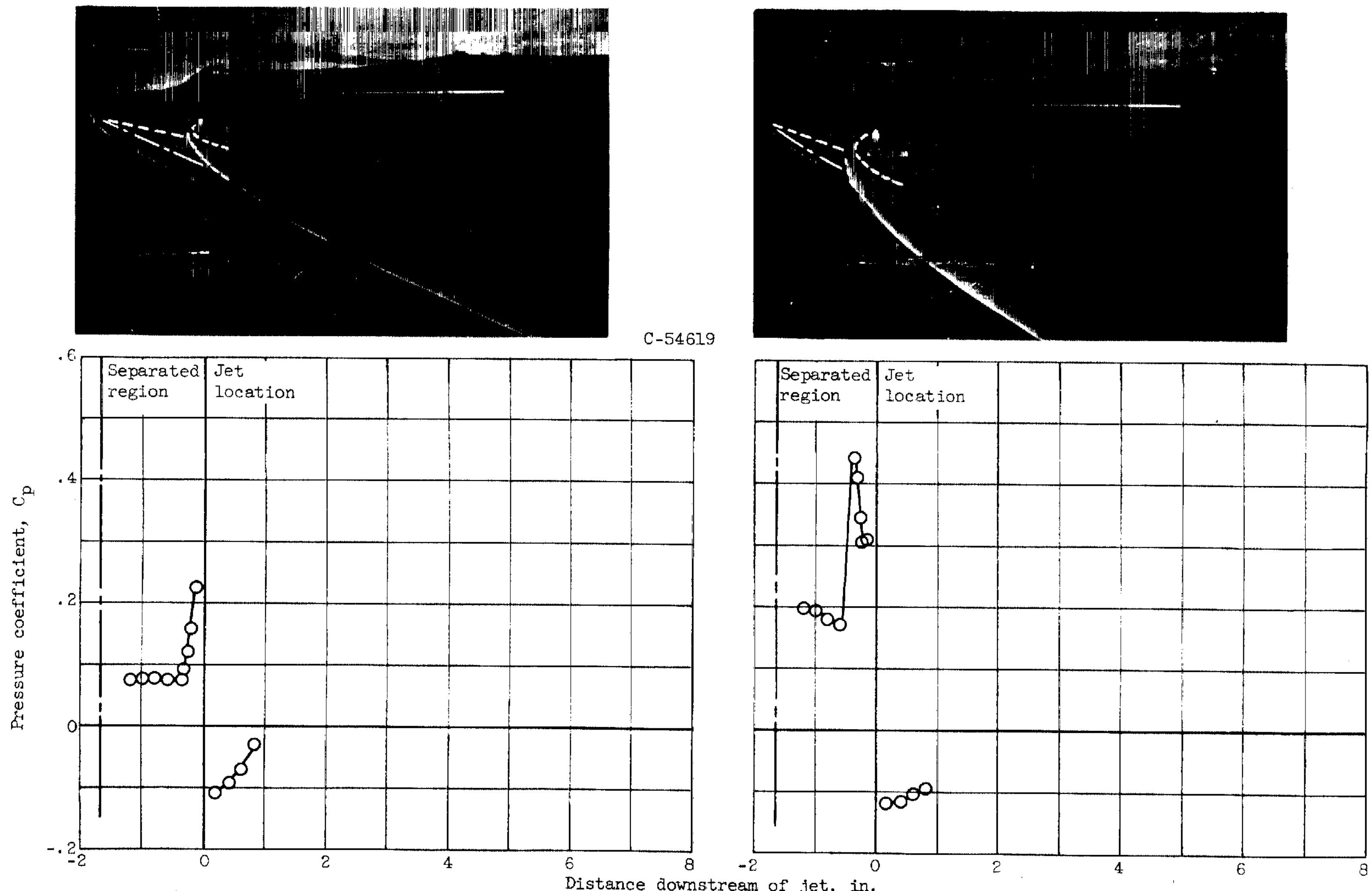


(c) $P_j/p_0 = 2643$.

Figure 5. - Concluded. Schlieren photographs of flat-plate configuration at Mach number of 2.92 and Reynolds number of 0.84×10^6 per foot.



(a) $P_j/p_0 = 161$.

(b) $P_j/p_0 = 1476$.

Figure 6. - Schlieren photographs of arrow-wing configuration at Mach number of 2.92 and Reynolds number of 1.53×10^6 per foot.

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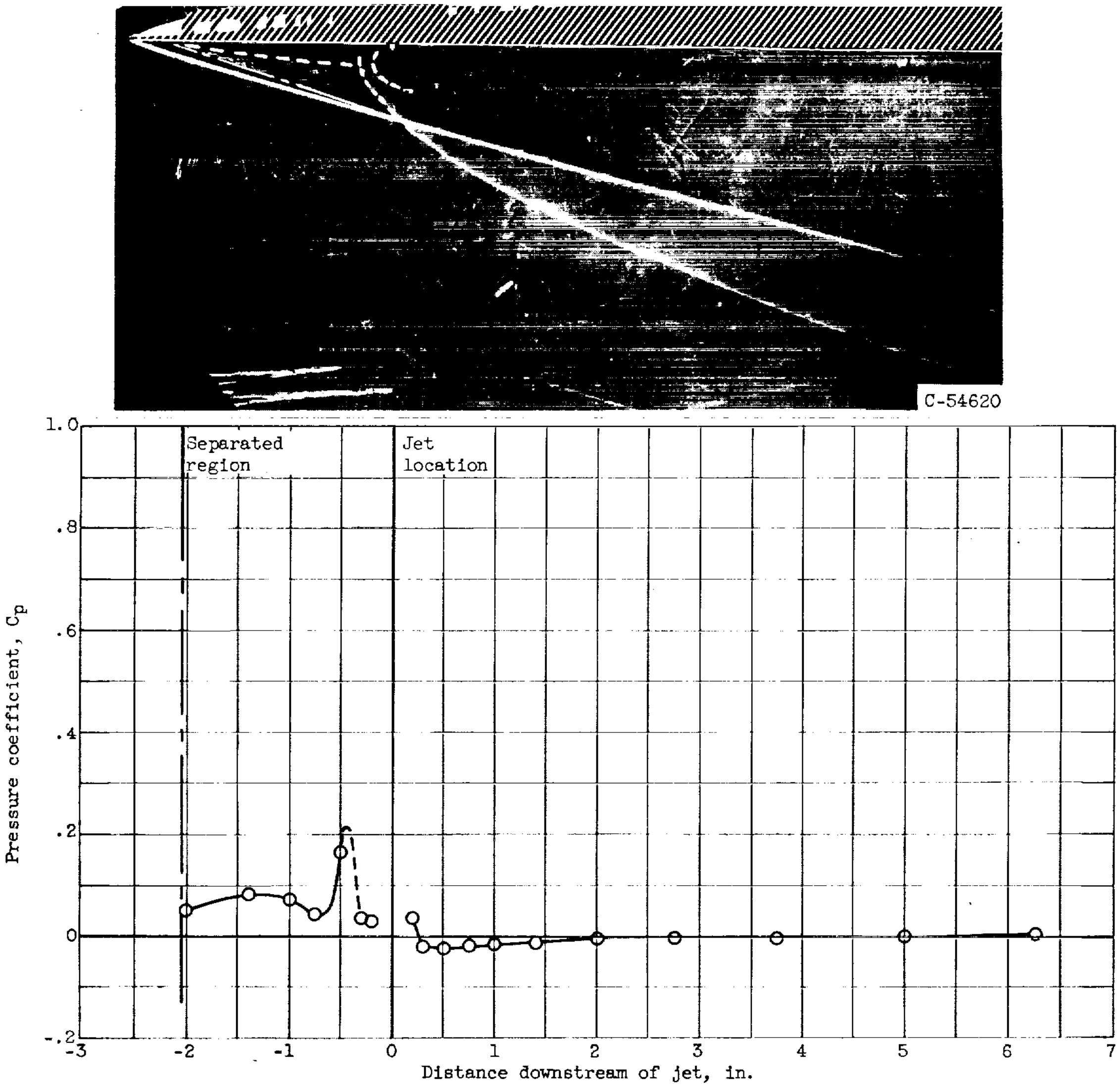
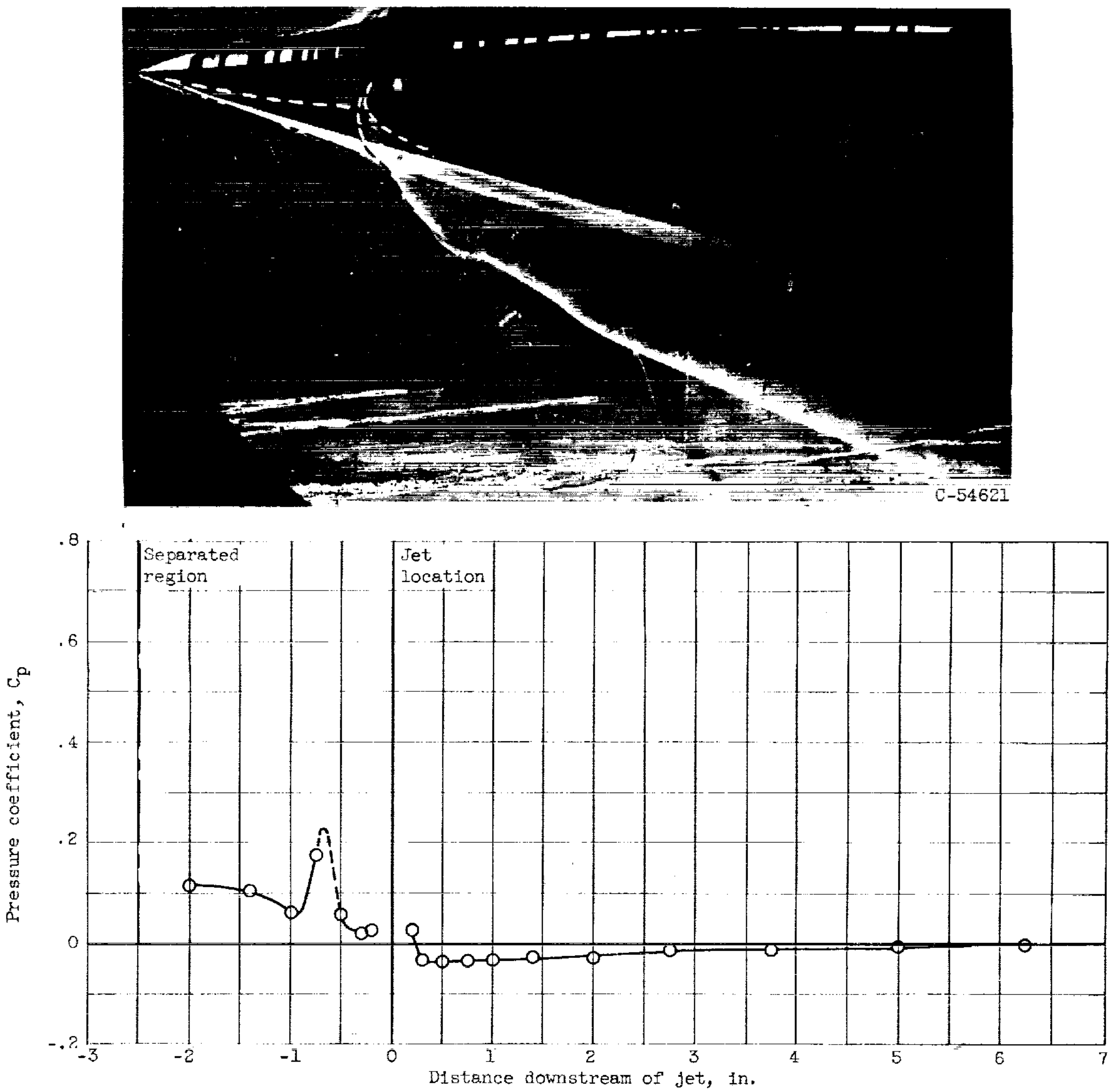


(a) $P_j/p_0 = 1406$.

Figure 7. - Schlieren photographs of flat-plate configuration at Mach number of 4.84 and Reynolds number of 1.4×10^6 per foot.



(b) $p_j/p_0 = 3811$.

Figure 7. - Continued. Schlieren photograph of flat-plate configuration at Mach number of 4.84 and Reynolds number of 1.4×10^6 per foot.

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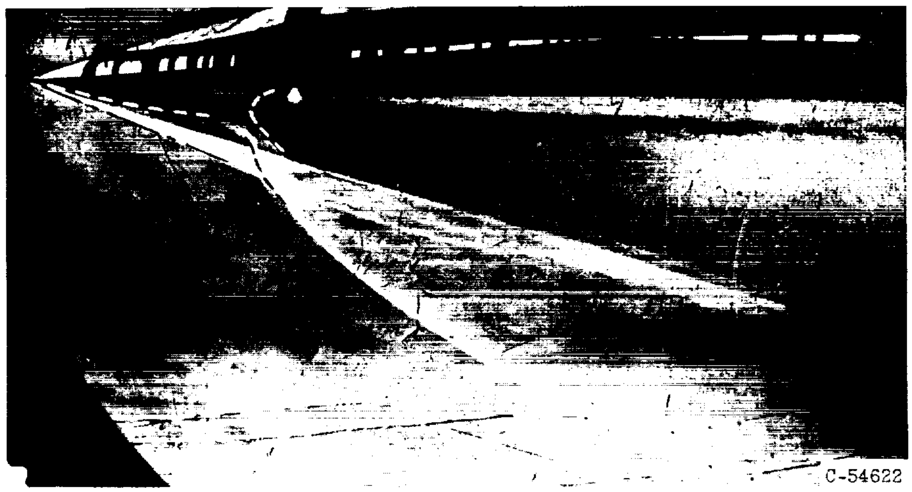
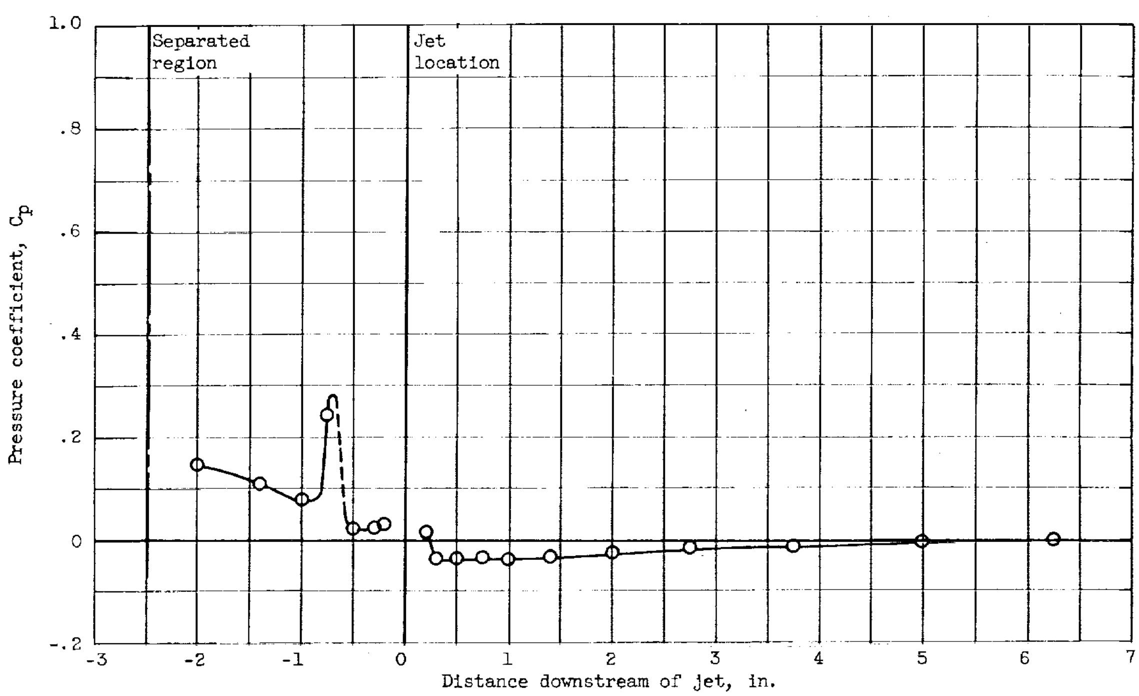
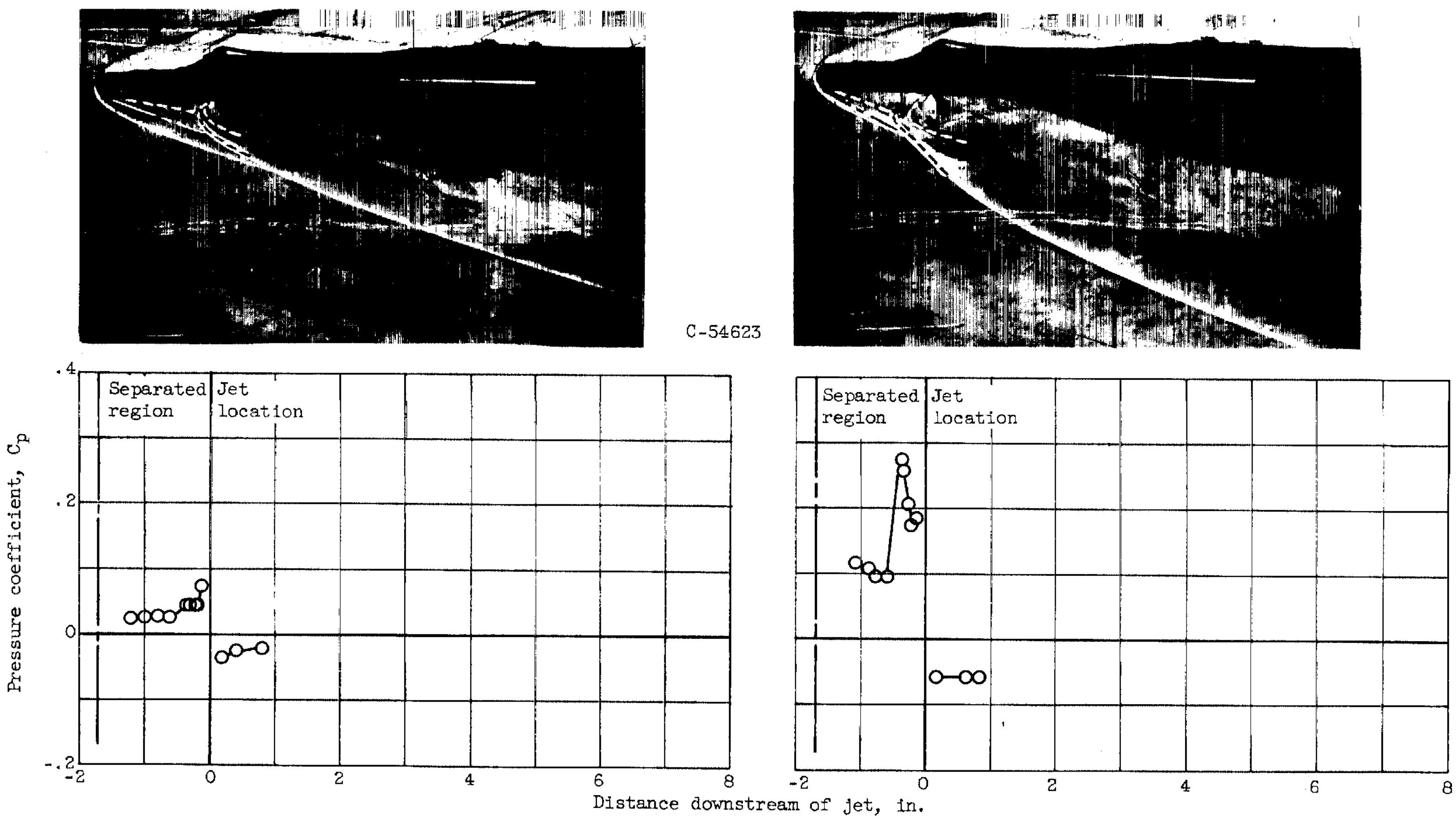




(c) p_j/p_0 = 5508.

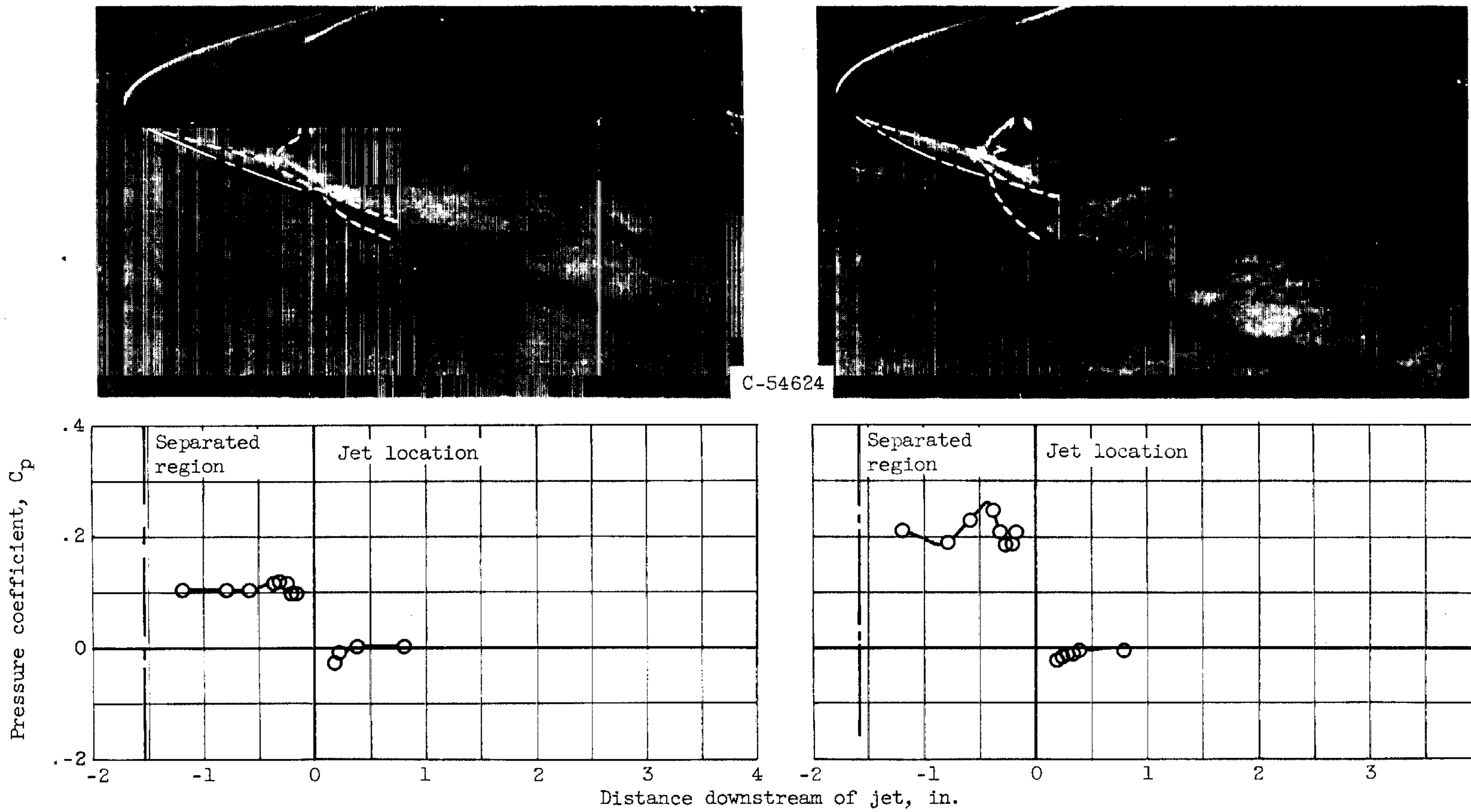
Figure 7. - Concluded. Schlieren photograph of flat-plate configuration at Mach number of 4.84 and Reynolds number of 1.4×10^6 per foot.



(a) $P_j/p_0 = 245.$

(b) $P_j/p_0 = 2150.$

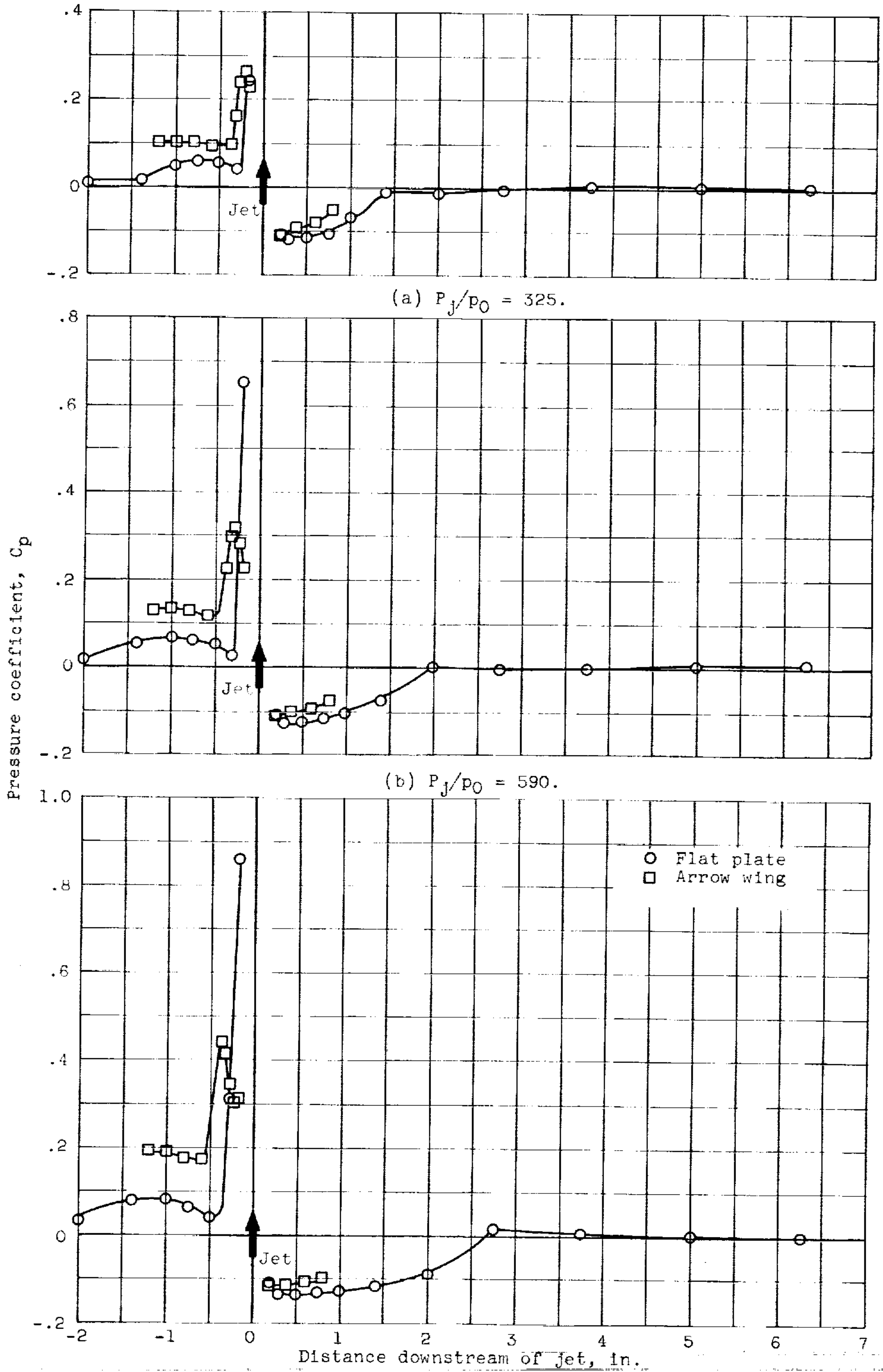
Figure 8. - Schlieren photographs of arrow-wing configuration at Mach number of 4.84 and Reynolds number of 3.01×10



(a) p_j/p_0 = 1239.

(b) p_j/p_0 = 5453.

Figure 9. - Schlieren photographs of arrow-wing configuration at Mach number of 6.4 and Reynolds number of 7.78×10^6 per foot.



(c) P_j/p_0 = 1247.

Figure 10. - Comparison of centerline pressure distributions between flat-plate and arrow-wing configurations at Mach number of 2.92 and Reynolds number of 1.88×10^6 per foot.

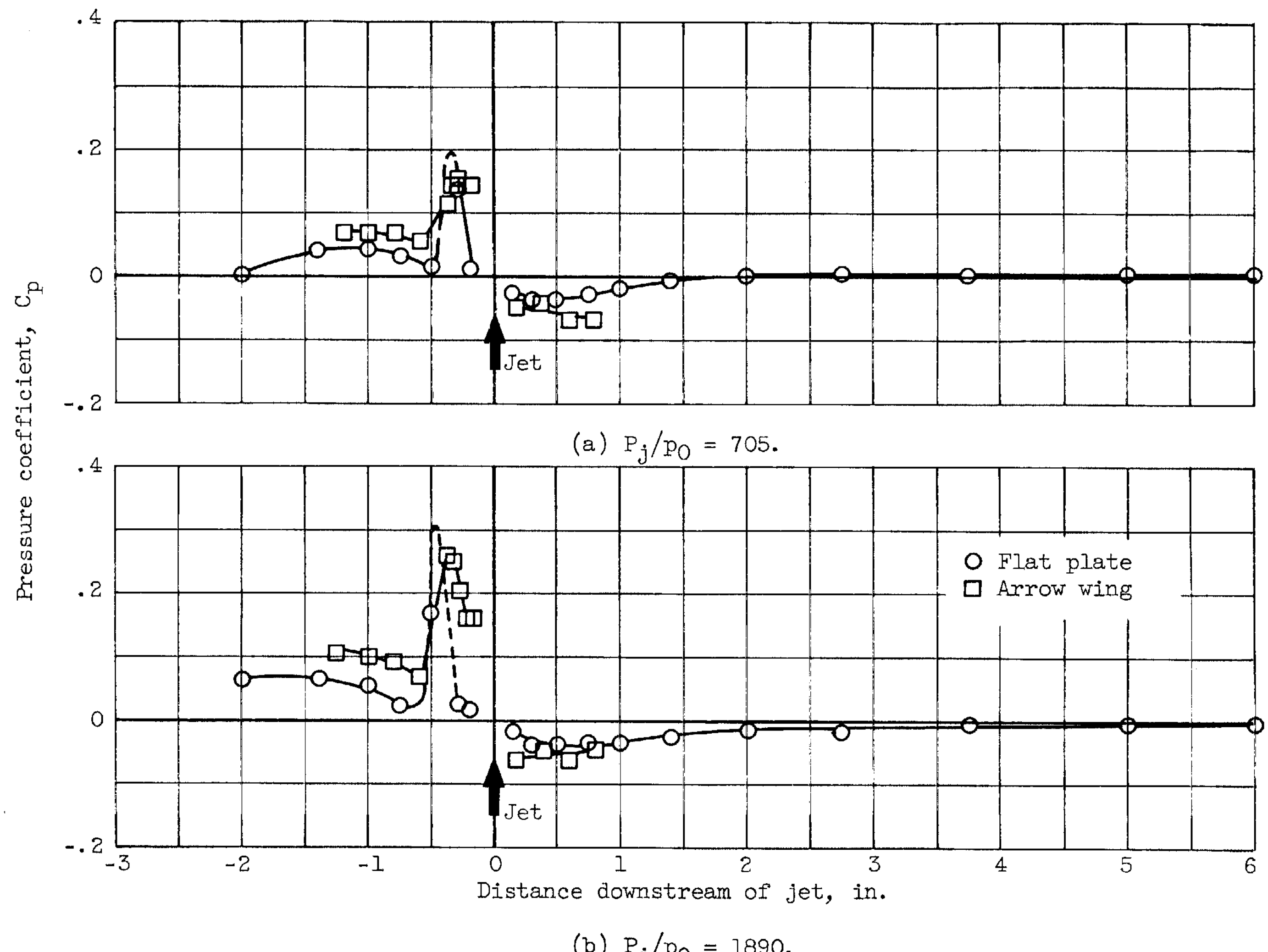
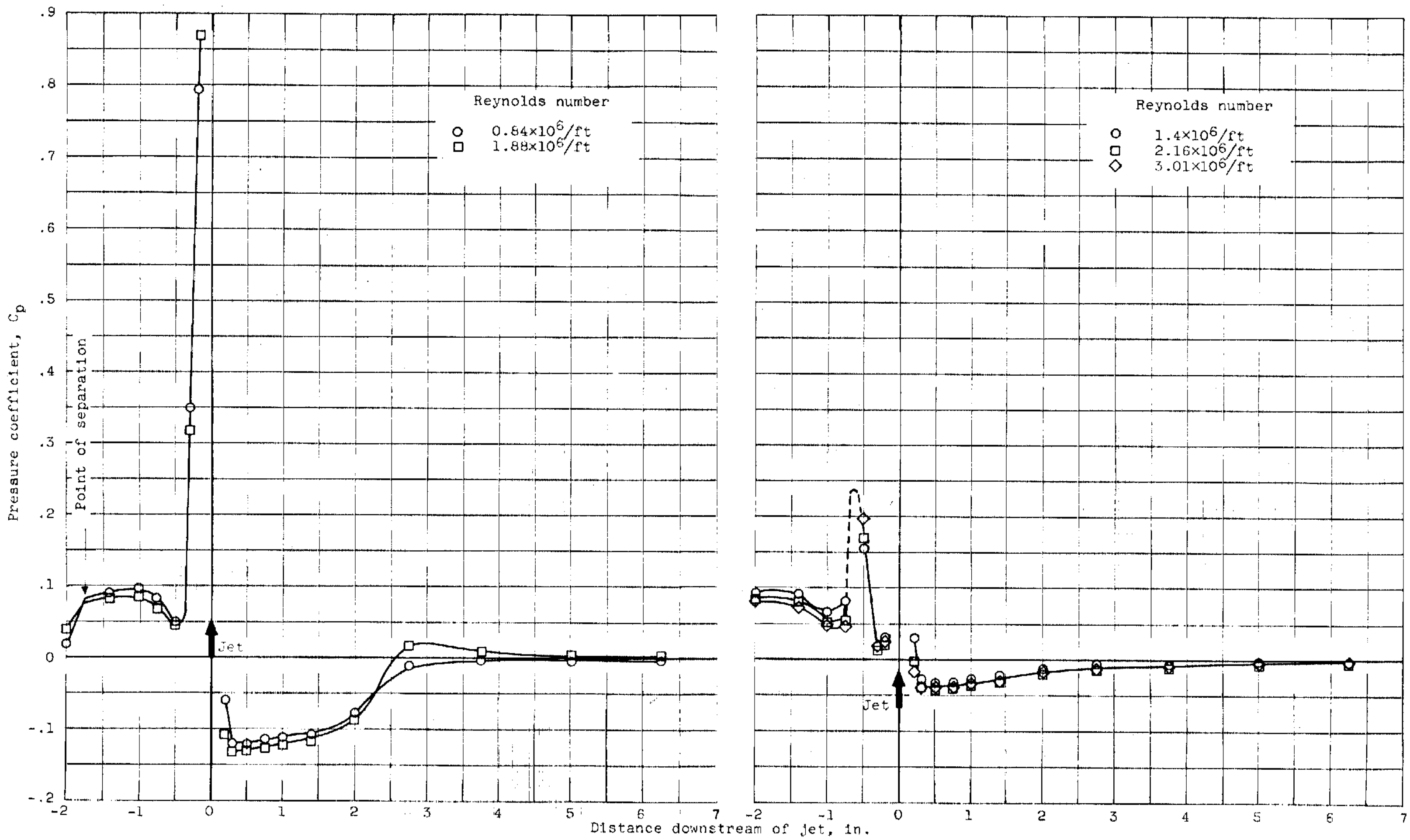


Figure 11. - Comparison of centerline pressure between flat-plate and arrow-wing configurations at Mach number of 4.84 and Reynolds number of 3.01×10^6 per foot.



(a) Free-stream Mach number, 2.92; p_j/p_0 = 1250; flat plate.

(b) Free-stream Mach number, 4.84; p_j/p_0 = 2660; flat plate.

Figure 12. - Effect of Reynolds number on centerline pressure distributions on flat-plate and arrow-wing configurations.

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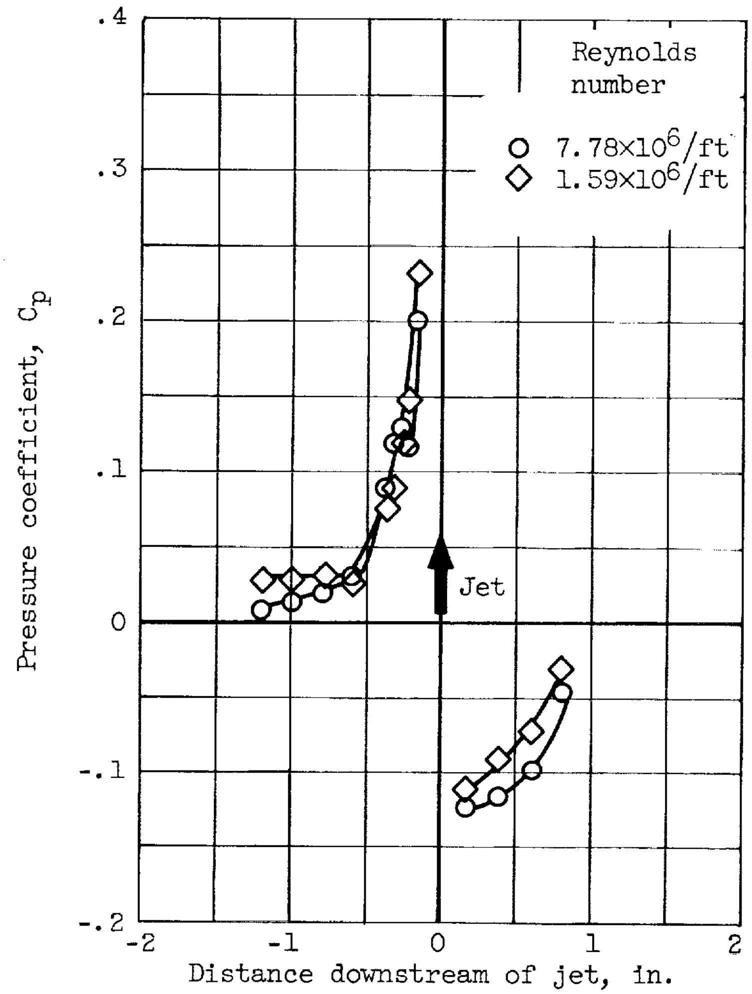
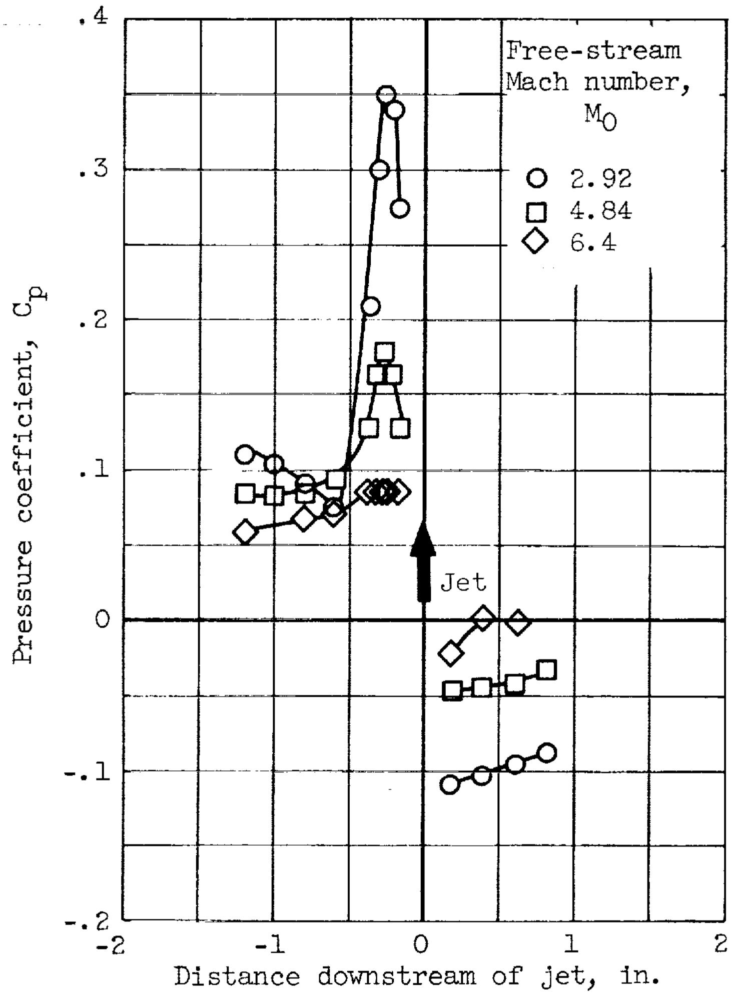


(c) Free-stream Mach number, 2.92; $P_j/p_0 = 766$; arrow wing.

Figure 12. - Concluded. Effect of Reynolds number on centerline pressure distributions on flat-plate and arrow-wing configurations.



(a) $P_j/p_0 = 605$; arrow wing.

Figure 13. - Effect of Mach number on centerline pressure distributions on flat-plate and arrow-wing configurations.

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An investigation was conducted to determine the effect of free-stream Mach number, jet pressure ratio, and Reynolds number on the surface pressure distributions caused by a sonic jet exiting normal to a flat surface. This jet was located near the leading edge of a sharp-edge flat plate and near the blunt nose of an arrow-wing configuration. The results indicate that jet pressure ratio (161 to 5508) had considerable effect on the surface pressure distributions. Also, at constant pressure ratio, the free-stream Mach number (2.92 to 6.4) produced a large effect, while the effect of Reynolds number over the limited range investigated was small.

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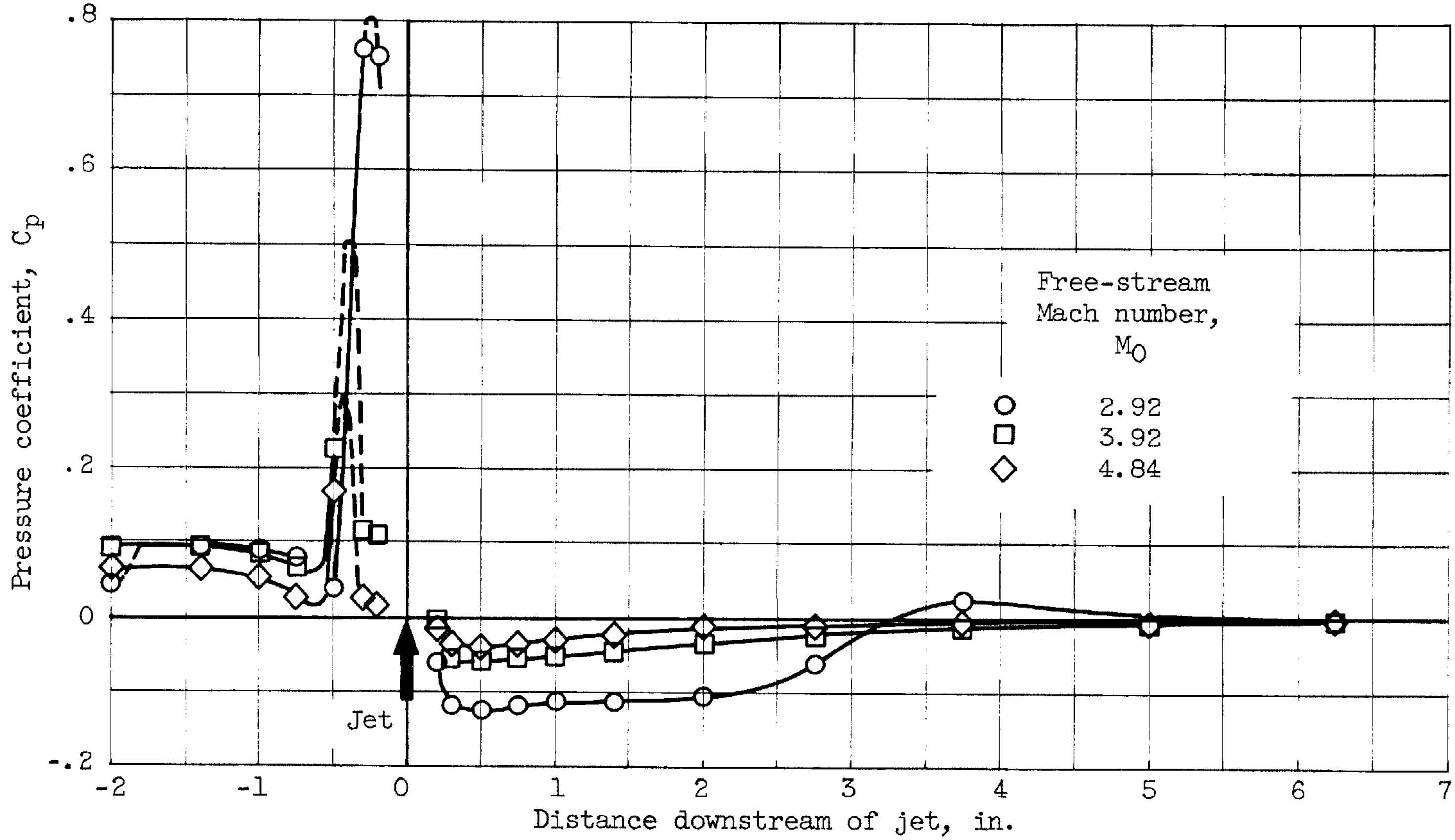

(b) P_j/p_0 = 1850; flat plate.

Figure 13. - Concluded. Effect of Mach number on centerline pressure distributions on flat-plate and arrow-wing configurations.